TABLE 3 –SUMMARY OF CONTROLS REQUIRED

All vessels and associated piping (H2, vacuum, helium):

Design to approved Functional and Operational Requirements and Design Plan that includes:

Design to ASME Codes
Consideration of high reliability and leak-tightness under both pressure and vacuum.
Capability to contain full rupture of LH2 vessel and withstand rupture(s) of adjacent vessels.
Capability of vessels to withstand external pressures as appropriate.
Vent lines and relief valve capacity capable of handling maximum credible gas load from insulating system failures.
Using highest pressure and thickest materials consistent with physics goals
Using ASME code relief valves or devices with equal reliability.
Using ductile materials for all vessels at all temperatures.
Using mechanical gauges as appropriate.
Using Power-To-Close valves where appropriate.
Using Power-To-Open valves where appropriate.

Weld all joints wherever possible.
Using high reliability components

For piping outside cave that is difficult to enclose in helium jacketing, build from very strong, reliable components. Provide mechanical guards to protect from damage.

Verify design with independent FEA analysis.
Build and test to approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.).

H2 gas handling system:

Design to approved Design Plan that includes consideration of high reliability and leak-tightness under both pressure and vacuum. Design relief system appropriately for gas supply system failure. Build and test to approved QA Plan. For piping outside cave that is difficult to enclose in helium jacketing, build from very strong, reliable components. Provide mechanical guards to protect from damage.

Helium gas handling system:

Design pressure control and relief system appropriately to avoid high external pressures on vacuum jacket.
Design helium jacketing relief system appropriately for He supply system failure.

Enclose weld joints and o-ring seal areas inside cave in helium jacketing so that vacuum space will be filled with helium, not air. Thus, vacuum leaks will draw in helium instead of air, hydrogen leaks will leak into helium instead of air, and there will be one more level of containment for hydrogen components inside the cave.

Control of contamination in H2 gas:

Have cleanup components in H2 gas handling system.
Use certified clean feed gases.
Use approved procedures to remove contaminants from H_2 input gas before cool-down.
Have helium purge on discharge side of all relief devices.

Control of contamination in vacuum and helium spaces:

Have helium purge on discharge side of all relief devices.

Provide LH2 “fast empty” system to quickly remove hydrogen in case of emergencies.

Interlocks:

LH_2 “fast empty” system interlocked to fire alarm,.
Target pressure and temperature sensors interlocked to alarm and possibly to refrigerator

shutoff.
Target temperature controller interlocked to refrigerator operation and/or flask temperature.
Vacuum valve(s) interlocked to vacuum or pump operation. Mechanically lock valves as appropriate.

Vent stack:
Locate vent stack in safe area.
Put vent line check valve close to exit to minimize length/volume of air/H2 mixture.
Purge line between relief valves and check valve with helium .

Operate entire H2 target system per approved procedures, including QA aspects (e.g., use thorough leak check procedures before each run).
Good housekeeping.
All personnel out of cave during power outage.

Local fire extinguishers

Risk management

- **Plan**
- **Failure analysis**

Drawings

The drawings for the LH2 target are saved on a website at IUCF

Hydrogen Safety Committee Reports

Safety Committee report and initial response to issues raised.

This is our first response to the report of the 2nd NPDG LH2 target safety review.
Our collaboration is very satisfied to the professionalism, dedication, and commitment of the Committee. The NPDG collaboration is determined to construct and operate an absolutely safe LH2 target at the Lujan Center. Our determination to have the most optimal and safe LH2 target is demonstrated by the steps that the collaboration has already taken; we have had two separate independent engineering analysis of the target cryostat design – conceptual and final - we have gone through already two target safety reviews. The first review was for the conceptual safety of the target and the 2nd review focused to the final design of the target cryostat. There will be the 3rd review that will deal with facility interface and target operational safety issues.

Below please find our first response to the report of the 2nd NPDG LH2 review. We have chosen to respond first in general terms, with a more detailed response to follow.
We have included the full text of the committee report and responded to each issue as it is raised in the report. Our responses are in **boldface.**

Mike Snow
Hermann Nann
Bill Lozowski
Mike Gericke
Igor Kuznetsov
Seppo Penttila

AGENDA AND DESCRIPTION OF SYSTEM

The committee met at the Indiana University Cyclotron Facility (IUCF), Bloomington, Indiana, on December 4-5, 2001. The charge to the committee was given by the LANSCE-12 Group Leader, Alan Hurd:

The Committee is asked to report to the LANSCE-12 group leader, Alan Hurd.
The Committee is asked to;

- Provide an independent review of the hydrogen safety aspects of the Liquid Hydrogen Target System of the np->dγ experiment on flight path 12 at LANSCE with priorities of protecting people (highest), protecting equipment and providing reliable operation.
- Provide an overall assessment of and recommendations for improvement of proposed hardware, procedures and facilities, including such aspects as design, controls, instrumentation, interlocks, safety systems, ease of operation and reliability.
- Review a list of possible failures and comment whether each is adequately represented and consequences correctly assessed, if the proposed mitigation method is adequate, if there is a better mitigation method, and if any failures have been overlooked.
- Comment on whether all physical phenomena or physical behaviors with significant safety or operational consequences had been adequately considered.
- Comment on any other safety or operational issues observed.

The committee members were:

(1) James Knudson, LANL LANSCE-7, Chair
(2) James Kilmer, Fermi National Laboratory
(3) Trevor Lucas, Oak Ridge National Laboratory
(4) Mike Seely, Jefferson National Laboratory
(5) William Schneider, retired, formerly with Brookhaven and Jefferson National Laboratories

Indiana University faculty, staff and students present:

- Mike Snow, IU Physics Department faculty
- Hermann Nann, IU Physics Department faculty
- Igor Kusnetsov, IUCF postdoctoral fellow
- Bill Lozowski, IUCF staff, target expert
- Mike Gericke, IU Physics Department graduate student

Los Alamos facility staff present:

- Dan Seely, LANL LANSCE-FM, TA-53 Facility Manager
- Roger Klaffky, LANL LANSCE-12, Lujan Facility Experimental Area Manager
- Seppo Penttilä, LANL P-23, NPDGamma Project Manager
- Jeff Schinkel, LANL P-23, Group Safety Officer
- Jan Novak, retired from LANL, Laboratory consultant for cryogenics

The meeting began with welcoming remarks by IUCF director John Cameron, who discussed the changes occurring to that facility as a result of the conversion of IUCF from an NSF facility to a state-supported medical treatment facility. This change has opened other opportunities and facilitated experiments at other facilities in user mode; hence the participation of the IU team in NPDGamma.

The review began with presentations of the present status of the $\vec{n}p \rightarrow d\gamma$ experiment, NPDGamma, the requirements and limitations placed on the target by the needs of the experiment, facility requirements, target safety and design, and details of the design of several safety-related components of the target.

Seppo Penttilä, the Project Manager for NPDGamma, described the present status of the experiment. The collaboration was scheduled beam time during Fall 2001 to develop beam monitoring equipment, the neutron spin flipper, and the CsI detector. This work has been progressing satisfactorily. The collaboration expects to begin work on building the shielding enclosure beginning January 2002, with target fabrication beginning at about the same time. The plan for commissioning the target in Los Alamos calls for this to happen in May 2003. At the request of the DOE, the collaboration is implementing full project management for the construction and operation of the experiment.

The design goals for the target were given by Mike Snow of IUCF. In order to meet the physics goals of the experiment, the target must:

- Capture >50% of the incident neutrons while shielding the gamma detectors (this implies a low-Z target)
- Maintain the neutron spin
- Introduce no systematic effects from polarized-neutron capture on other materials present
- Introduce no noise effects above $\sqrt{N_\gamma}$ from fluctuations in target pressure, temperature or density (implies that bubbles must be suppressed)
- Minimize the magnetic interactions between the target and the polarized neutrons that could affect the overall level of polarization
- Be safe and reliable to operate

SUMMARY OF REVIEW FINDINGS

The sense of the committee is that the basic target design concept is sound and that the target would work as proposed by the collaboration and would likely meet the criteria required of the experiment. A number of details are still to be worked out, and the committee should be consulted when all of the final decisions have been made. With the basic design under control, the committee was able to put a significant emphasis on operational considerations for this target; where it was generally felt that the most likely source of difficulty that will arise from the operation of this target will be from operator error. No other significant failure modes were identified by the committee.

First and foremost, the committee agrees that a quality assurance (QA) plan should be established as required by the management plan being implemented. The QA program will need to meet the requirements of the relevant DOE orders while ensuring that the resulting system also meets the intent of the electrical and fire codes, and ANSI B31.3 for the system piping. The committee requests that the designers provide a statement describing how the various vessels will meet the intent of the ASME pressure vessel Code standards along with LANL requirements.

Response: the QA issue is very important part of our planning and covers a broad range of issues starting from the facility authorization basis down to detailed planning of the target testing. The QA Plan is in preparation. We have made significant progress in

assembling documentation for this QA plan through the construction of our NPDG LH2 Target Engineering Document (TED), where the full QA Plan will be presented. The TED contains all design information and technical documentation for the target.

The vessels will meet the intent of the ASME pressure vessel code by designing all vessels to ASME requirements, by constructing the target using approved welders, by radiographing welds and certifying all materials used, and by pressure testing at IUCF. In the TED we will have at the end of every section that deals with different target vessels, a summary chapter that explains how the ASME code is met and if there is any exceptions to the Code. When the we have the QA Plan it will be sent to the Committee for approval.

RECOMMENDATIONS FOR THE TARGET DESIGN

1. Operational considerations:

A number of issues arose regarding target operations that the committee felt the need to comment about:

- The committee was concerned that the presence of the 10 kW heater called for in the present design is a potential source of trouble. It is intended to assist in the rapid venting of hydrogen in the event of an abnormal situation, but the (conservative) calculations of the design team indicate that there is little benefit to be gained in turning on this heater over such other solutions as spoiling the insulating vacuum or simply turning off the cryo-coolers. The committee viewed the consequences of an unplanned or inadvertent activation of this heater while the target flask is empty, causing severe damage to the vessels, to outweigh the small benefit gained in the venting scenario. The committee recommends that the design team investigate alternative methods of initiating the rapid vent.

Response: We are not going to install the 10kW heater. Instead we plan to implement rapid venting of the target by turning off the refrigerators and introducing a controlled amount of dry nitrogen gas into the main vacuum chamber. The nitrogen will transfer heat efficiently from the target to the outside environment through both the thermal conduction of the gas and also the latent heat of the nitrogen liquid-gas phase transition. We are performing an estimate of the expected time for target venting. The venting method will be thoroughly tested and results recoded. The design and test results will be sent to the Committee for approval.

- While some members of the committee have successfully operated sub-atmospheric cryogenic systems, no one was aware of a hydrogen target being operated in this fashion. To the best of the committee's understanding the sub-atmospheric operating principle presented did not appear to work. It was the committee's conclusion that operating at less than one atmosphere invites a host of difficulties should leaks develop, despite the large size of the proposed vent lines. The committee recommends that the target philosophy be modified so that the target operates at greater than 1.25 bar rather than at sub-atmospheric pressures, and that the collaboration give a clear explanation of the operating principles involved. If the return line from the target is returned to the main manifold at a point below the gas feed/vent connection, the liquid will subcool and a small heater can be used to control its operating temperature. With subcooling of about 4K, boiling in the target is unlikely and the outer refrigerated radiation shield should no longer be required.

Response: We plan to implement this recommendation by simply filling the target and the entrance and exit lines until the liquid-gas phase boundary is located in an area where the vapor pressure is 1.25 bar. This can be done with minimal changes in the design of the target piping.

On the question of whether or not the radiation shield/second refrigerator is still needed: we are performing new heat flux estimates for this changed configuration to make sure that we can still cool the target with the increase in the heat leak due to the higher liquid level in the fill and vent tubes. The second refrigerator may still be required for this reason.

The final design and test results will be sent to the Committee for approval.

- Considerable discussion revolved around the possibility of using a storage tank to contain the charge of hydrogen, rather than relying on a manifold and rack of up to six hydrogen bottles. Given the expected 48-hour cooldown time to fill this target, it was felt that a storage tank would be advantageous in that bottle changes at all hours would be eliminated, and, given a clean tank, that overall cleanliness of the charge could be better maintained. Recognizing that some serious logistical details would need to be worked out, the committee recommends that the use of a storage tank large enough to contain the entire hydrogen inventory be investigated. The inclusion of such a tank would have consequences on other parts of the system, and perhaps also other parts of the Lujan facility, that would have to be thought through. Additionally, the committee suggests that a warm buffer or ballast tank would ease the cooldown process by smoothing out the fast pressure transients that would likely occur during cooldown.

Response: We have looked into the possibility of using a storage tank at LANL. We have such a tank at IUCF that has been cleaned internally. The problem is that the size of the target (20 liquid liters) means that the volume of gas at room temperature is very large compared to the size of high pressure gas bottles, and any compressor that is added to make the use of a smaller container possible will add another possible failure point in the system. Furthermore, any such system has to be located outside the ER-2 area 40-50 yards away from the target , and therefore the use of either gas bottles or a dump tank will require long lines - the dump tank requires also a six inch diameter line - from outside the building to the experimental area. We are still evaluating this concept. The issue has been also introduced to the Facility Management and to the fire marshal.

The final design and conclusions will be sent to the Committee for approval.

After the safety meeting, we have become aware of the existence of commercially-available hydrogen gas generators which produce hydrogen gas at the pressures, flow rates, and purities required for filling the target. These gas generators produce hydrogen by electrolysis from deionized water and are compact, automatic devices which incorporate a palladium leak purifier which we had proposed to include on the gas handling system. The use of such a system would simplify both the gas handling system design and the connection between hydrogen source and experiment location, which could be shortened substantially thereby reducing the risks associated with a long high-pressure hydrogen

gas line in ER2. We are therefore redesigning the gas handling system to incorporate this element into the design. If the hydrogen generator will be our solution for the target hydrogen supply, we will initiate a change process as defined in this report.

2. Relief setpoints:

The committee and the design team spent a significant amount of time discussing the choice of set points for the relief valves on the both the hydrogen flask and the helium jacket. These settings appear to be far above the operating pressure, be it either less than or greater than one atmosphere, and are greater than the crush pressure of the vacuum jacket. Recognizing that the final settings could be affected by whether or not a storage tank is chosen, the committee wishes to see a thorough description of the philosophy and rationale behind the eventual relief valve settings. The committee recommends that relief valve pressure settings be included with the piping schematics so that values will be unambiguous.

Response: This will be done. A detailed gas handling schematic along with the operating pressures and set points will be provided to the committee.

3. Vent line sizing:

The size of the hydrogen vent line was one topic revisited by the committee in its concluding discussions. This discussion is also a consequence of the lack of understanding on the committee's part concerning the basic principles of operation proposed. It was not immediately clear that venting hydrogen would warm sufficiently to be buoyant when it reaches the end of the vent stack. Clearly the design team needs to perform new calculations of the vent line conductance once the vent line design is finalized. The committee recommends that the design team review the size of the vent line considering the following points concerning the cold gas in the line;

- The ortho-hydrogen to para-hydrogen ratio of recondensing gas may be sufficiently changed from the target liquid as to make maintaining the desired ortho/para ratio difficult. However, operating the system with sub-cooled liquid, as suggested, would improve control of the ortho/para ratio since the constant body of fluid is not required to condense and re-condense.
- The heat leak back into the target flask needs to be of manageable proportions.

Response: We are looking into how to ensure that the gas close to the end of the vent stack continues to exit instead of sinking back down the pipe. This may involve the use of heaters in the upper areas of the vent pipe.

The final design will be provided to the Committee for approval.

We estimate that, in the absence of a strong catalyst for that portion of the recondensing hydrogen located in regions whose temperature is larger than 17K, there will be negligible back-conversion of para to ortho. The ortho-para catalyst will be held at a temperature of 17K and so the o-p ratio will eventually equilibrate to a value appropriate for this temperature. Once the hydrogen has been converted to para in the catalyst, the rate of back-conversion in the absence of a catalysy is very low.

We are reestimating the heat leak of the exit tube on the target for the proposed 1.25 bar operating conditions.

5. Pressure vessels:

Significant work remains to be done on the design of the hydrogen pressure vessel. The committee is satisfied that the present plan of bolting the upstream/downstream dome to the aluminum body of the vessel will work, and is also satisfied with the progress made at correcting the deficiencies with the entrance head pointed out by the analysis performed by ARES Corporation. The design team is encouraged to review the stiffening around the penetrations into the vessel for the fill and vent lines. The committee would like to see more analysis of the entire vessel, including the interactions between the vessel and its supports, the flange designs and of the outer vessels as well. The committee agrees with the design team that the transfer of the target to Los Alamos should be done with the target disassembled and properly packed. The design team is encouraged to perform a vibration analysis of the components during shipping to preclude damage.

Response: The ARES analysis not only pointed out stress concentrations in the first vessel design but also specified a design and an assembly procedure that would remove these stress concentrations and allow the vessel to meet the safety requirements. We therefore propose to construct the vessel following exactly the ARES recommendations and then proceed to testing.
The final design of the vessels and the final analysis results will be provided to the Committee for approval.

The target will rest on low thermal conductivity plastic inserts in such a way that it is free to move relative to the radiation shields and the main vacuum vessel. Furthermore the fill and vent lines of the target will include a section with flexible tubing to eliminate stresses due to differential thermal contraction.

Stiffening rings will be added to the outer vessel using the Code-approved calculational procedure.
The final design of the target support and couplings will be provided to the Committee for approval.

The target will certainly be shipped in separate pieces for assembly at LANL.

6. Testing:

The committee was concerned that the testing plan for the target is not complete. It does, however support the present idea that testing with inert liquid be done at IUCF in order to debug the gas handling system before everything is shipped to Los Alamos for final testing with hydrogen. The committee requests the opportunity to review the testing plan prior to implementation.

Response: We will certainly present the details of the testing procedure for review by the committee.

7. Gas handling system:

The committee was concerned that the conceptual design for the gas handling system is too vulnerable to operator error and disruption of target operations, especially during cooldown. The committee specifically identified the residual gas analyzer (RGA) as a potential source of trouble in that a valve line-up error or even leaky valves could cause either hydrogen or helium to enter the isolation vacuum. The committee recommends that the design team investigate alternative methods of installing or operating the RGA to prevent the former scenario. This should eliminate the cross-connect and move the RGA from one part of the system to the other. Two RGAs could be used to avoid the cross connection, or a dedicated pumping system designed for RGA to pump continuously. The proposed design also showed a palladium leak downstream of the cold trap; some concern was raised by the committee that the palladium would catalyze hydrogen and residual oxygen into water that would then plug the system. The committee recommends that the final design have the palladium filter upstream of the cold trap. The design presented to the committee was incomplete, with some potentially trapped volumes lacking pressure relief. Therefore, the committee requests that a new gas handling design that addresses these issues be developed, and a detailed full piping diagram be created to full engineering standards. Finally, the committee suggests that the eventual operating procedures that will be written include straightforward checks of system integrity such as rate-of-rise tests.

Response: Our plan is to use two RGA sensor heads, one on the main vacuum and one on the hydrogen fill line, to address this concern. We will also implement the palladium leak before the cold trap as requested. Indeed if the hydrogen generator is used the gas it produces at the exit has already passed through a palladium leak.

Operating procedures for the gas handling system will certainly be written and submitted to the safety committee for approval.

Redesign of the gas handling system to respond to these recommendations is in progress.

The final design of the gas handling system will be provided to the Committee for approval.

8. Code compliance:

Fire and electrical code issues are serious hurdles for operators of liquid hydrogen targets to overcome, as these codes do not address the special circumstances of these systems. The project must obtain the agreement of the appropriate authorities at Los Alamos before operating this target. The committee agrees that the construction of a tent to enclose the portion of the gas handling system located above the shielding cave is the best solution for isolating the hydrogen system from sparking electrical equipment. The committee felt that the potential for the ER-2 overhead crane to cause difficulties with the gas handling system can be minimized through the use of appropriate administrative controls on crane operations. The design team is encouraged to pursue this approach with the Los Alamos fire protection authorities. The suggested construction method of using Herculite (a self-extinguishing coated fabric) over a Unistrut framework with a vented fan drawing air through the enclosure has been used successfully by most of the committee members at their home institutions. Since final acceptance of this system will be made by LANL, the committee does not need to be involved in any further review of this subject beyond being assured that a tent is implemented.

Response: We will implement the tent over the gas handling system. An approach for the safety of the gas handling system is discussed with the Facility people and fire marshal. The final solution will be sent to the Committee.

9. Facility interface issues:

A discussion of facility interface issues covered areas that will require extensive interaction between the project and the relevant authorities at LANL. The potential exists for impacting the requirements of the authorization bases of actinide experiments and of the 1L Target Facility. It is clearly in the best interests of the experiment that any such negative interactions between the experiment and its neighbors in ER-2 be eliminated. The committee is of the opinion that the best way to achieve this goal is to develop the safest, most reliable target possible consistent with meeting the physics goals of the experiment. It will be up to the collaboration to convince the appropriate LANL and DOE authorities that the target design does indeed pose no threat to other experiments and to the facility. The failure table prepared for the engineering document that describes this target will be a key component of these discussions.

Response: We will continue to elaborate our failure table and address any questions raised at LANL with respect to interaction with other experiments. The committee was absolutely correct in raising the issue of the facility interface. The 2nd target safety review was planned to focus to the target vessel design issues and leave the facility issues to the 3rd review that will be done by the different combination of reviewers since we need more LANL experts for this committee.

The advanced Engineering Document of the target will be provided to the Committee. This will also include the updated failure analysis table.

10. Change control:

Change control is part of the larger issue of quality assurance (QA) that must be addressed by the project. The basis for all QA will be the Engineering Document, once finalized, being prepared by the project, and the assembly drawings. Any deviations from this basis, for whatever reasons, will be subject to the change control process. While the full details of this will be part of the project management plan, the committee recommends the following broad details be included in the change control process:

- When a change is identified, the Target Work Package Leader sends a written change request to the Project Leader. The change request will include sufficient detail to describe the change and full justification for the request.

- A Target Change Control Board (TCCB) consisting of J.D. Bowman (Experiment Spokesman), J. Knudson (Review Committee Chair), S. Penttilä (Project Manager), and J. Schinkel (P-23 Group Safety Officer) will review the change.

- The TCCB will either approve the change or recommend that it be forwarded to an appropriate level for further review and approval. The hierarchy of levels might be: TCCB, LANSCE Facility, LANL LH_2 Safety Committee, LANL management, DOE.

The TCCB will function mostly as a screening committee.

The committee requests that a final readiness review of the target be completed prior to the start of operations.

Response: We will follow these procedures for change control.

11. Approval to proceed with target fabrication:

Given the fact that a multi-institution collaboration is interacting with a DOE facility in this effort, the committee recommends that the following steps be undertaken before proceeding with fabrication of the target:

- A detailed response to this report is prepared and accepted by Alan Hurd, LANL LANSCE-12 Group Leader.
- A complete set of assembly drawings for the target and its support structure is prepared, signed off by IUCF authorities, and approved by the appropriate LANL authorities.
- That the Committee reviews the drawings and concurs with the detailed response to this report.

Reference list (H. Nann, M. Snow, 6-25-01)

The following references were consulted in the course of the preparation of this report:

[1] Safety Standard for Hydrogen and Hydrogen Systems, NASA report NSS 1740.16 (1997)

[2] NASA Glenn Safety Manual, Chapter 6: Hydrogen. NASA report (2000).

[3] Livermore ES&H Manual, Volume II, part 18: Pressure/Noise/Hazardous Atmospheres, UCRL-MA-133867, (2001)

[4] ASM Metals Reference Book, second edition, American Society for Metals, (1983).

[5] ASM Handbook, Vol. 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, (1993).

[6] Standard for Hydrogen Piping Systems at Consumer Locations, first edition, Compressed Gas Association, CGA G-5.4, Arlington, VA (1992).

[7] Hydrogen Vent Systems, Compressed Gas Association, CGA G-5.5, Arlington, VA (1996).

[8] Pressure Relief Device Standards, Part 3-Compressed Gas Storage Containers, S-1.3 Compressed Gas Association, Arlington, VA (1995).

[9] ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2

[10] ASME B31.3 Code for Pressure Piping-Process Piping, American Society of Mechanical Engineers, New York (1996)

[11] Flow of Fluids Through Valves, Fittings, and Pipe, Crane Technical Paper No. 410, Crane

Co., New York, 1991.

[12] Standard Handbook of Engineering Calculations, Editors: T.G. Hicks, S.D. Hicks, and J. Leto, 3rd edition, McGraw Hill, New York, 1995.

[13] Cryogenic Process Engineering, K.D. Timmermans and T.M. Flynn, Plenum Press, New York (1989).

[14] NFPA 50A Standard for Gaseous Hydrogen Systems at Consumer Sites, National Fire Protection Association, Inc. (1994)

[15] NFPA 50B Standard for Liquified Hydrogen Systems at Consumer Sites, National Fire Protection Association, Inc. (1994)

[16] M. Wiseman et al., Applications of Cryogenic Technology, Vol. 10, Edited by J.P. Kelley, Plenum Press, New York, 287 (1991)

[17] D. H. Weitzel et al, Elastomers For Static Seals at Cryogenic Temperatures, Advances in Cryogenic Engineering 6, 219 (1961).

[18] C. Nake et al, Acta Physica Polonica B 24, 1572 (1993).

[19] Y. T. Borzunov et al, Cryogenics, 235 (1972).

[20] M. Hoenig, Advances in Cryogenic Engineering 14, Plenum Press, New York, 627 (1972).

[21] W. Schmidt and C. F. Williamson, Bates Internal Report #90-02 (1990).

[22] N. S. Sullivan et al, Cryogenics 30, 734 (1990).

[23] L. X. Jia et al, Advances in Cryogenic Engineering 43, 629 (1998).

[24] M. A. van Uden et al, preprint, submitted to NIM (1999).

Appendices

Appendix 1: Material Data Sheets

MatWeb.com, The Online Materials Database
Aluminum 6061-T6; 6061-T651

Subcategory: 6000 Series Aluminum Alloy; Aluminum Alloy; Metal; Nonferrous Meta

Close Analogs:

Composition Notes:
Aluminum content reported is calculated as remainder.
Composition information provided by the Aluminum Association and is not for design

Key Words: UNS A96061; ISO AlMg1SiCu; Aluminium 6061-T6, AD-33 (Russia); AA
6061T6, UNS A96061; ISO AlMg1SiCu; Aluminium 6061-T651, AD-33 (Russia); AA(

Component	Wt. %	Component	Wt. %	Component	Wt. %
Al	98.6 - 95.8	Mg	0.8 - 1.2	Si	0.4 - 0.8
Cr	0.04 - 0.35	Mn	Max 0.15	Ti	Max 0.15
Cu	0.15 - 0.4	Other, each	Max 0.05	Zn	Max 0.25
Fe	Max 0.7	Other, total	Max 0.15		

Material Notes:
Information provided by Alcoa, Starmet and the references. General 6061 character
uses: Excellent joining characteristics, good acceptance of applied coatings. Combi
relatively high strength, good workability, and high resistance to corrosion; widely av
The T8 and t9 tempers offer better chipping characteristics over the T6 temper.

Applications: Aircraft fittings, camera lens mounts, couplings, marines fittings and h
electrical fittings and connectors, decorative or misc. hardware, hinge pins, magneto
brake pistons, hydraulic pistons, appliance fittings, valves and valve parts; bike fram

Data points with the AA note have been provided by the Aluminum Association, Inc.
NOT FOR DESIGN.

Physical Properties	Metric	English	(
Density	2.7 g/cc	0.0975 lb/in_	/

Mechanical Properties

Hardness, Brinell	95	95	AA; Typ load;
Hardness, Knoop	120	120	Converted f Hardr
Hardness, Rockwell A	40	40	Converted f Hardr
Hardness, Rockwell B	60	60	Converted f Hardr
Hardness, Vickers	107	107	Converted f Hardr
Ultimate Tensile Strength	310 MPa	45000 psi	/
Tensile Yield Strength	276 MPa	40000 psi	/
Elongation at Break	12 %	12 %	AA; Typic (1.6 mm)
Elongation at Break	17 %	17 %	AA; Typi (12.7 mm
Modulus of Elasticity	68.9 GPa	10000 ksi	AA; Typica of te coı Compressio is about than tensile
Notched Tensile Strength	324 MPa	47000 psi	2.5 cm w cm thick si specime
Ultimate Bearing Strength	607 MPa	88000 psi	Edge d dian
Bearing Yield Strength	386 MPa	56000 psi	Edge d dian
Poisson's Ratio	0.33	0.33	Estimated f in simila
Fatigue Strength	96.5 MPa	14000 psi	AA; 5(cycles reversed machine
Fracture Toughness	29 MPa-m_	26.4 ksi-in_	K_{IC}; TL (
Machinability	50 %	50 %	0-1(Alumi
Shear Modulus	26 GPa	3770 ksi	Estimated f
Shear Strength	207 MPa	30000 psi	/

Electrical Properties

Electrical Resistivity	3.99e-006 ohm-cm	3.99e-006 ohm-cm	AA; Typi

Thermal Properties

CTE, linear 68°F	23.6 µm/m-°C	13.1 µin/in-°F	AA; Typica over 68-21
CTE, linear 250°C	25.2 µm/m-°C	14 µin/in-°F	Estimated f in similar Al
Heat Capacity	0.896 J/g-°C	0.214 BTU/lb-°F	
Thermal Conductivity	167 W/m-K	1160 BTU-in/hr-ft_-°F	AA; Typi
Melting Point	582 - 652 °C	1080 - 1205 °F	AA; Ty based com wrought pr inch th greate melt completely by homo
Solidus	582 °C	1080 °F	A
Liquidus	652 °C	1205 °F	A

References are available for this material.

MatWeb.com, The Online Materials Database
Aluminum 6061-T6

Subcategory: 5000 Series Aluminum Alloy; Aluminum Alloy; Metal; Nonferrous Meta

Close Analogs: Four other tempers of this alloy are in the database.

Key Words: UNS A95083; ISO AlMg4.5Mn; Aluminium 6061-T6; AA6061-T6

Component	Wt.	Component	Wt. %	Component	W
Al	94.8				

Al	94.8	Fe	Max 0.4	Si	M 0
Cr	0.05 - 0.25	Mg	4 - 4.9	Ti	M 0.
Cu	Max 0.1	Mn	0.4 - 1	Zn	M 0.:

Physical Properties	**Metric**	**English**	**(**
Density	2.66 g/cc	0.0961 lb/in_	
Mechanical Properties			
Hardness, Brinell	77	77	500 kg load with Calc
Hardness, Knoop	100	100	Converted from Brin
Hardness, Vickers	87	87	Converted from Brin
Tensile Strength, Ultimate	290 MPa	42100 psi	
Tensile Strength, Yield	145 MPa	21000 psi	
Elongation at Break	22 %	22 %	In 5 cm; Sample 1
Modulus of Elasticity	70.3 GPa	10200 ksi	
Notched Tensile Strength	269 MPa	39000 psi	2.5 cm width x 0.16 cn notched specim
Ultimate Bearing Strength	552 MPa	80100 psi	Edge distance/pin di
Bearing Yield Strength	248 MPa	36000 psi	Edge distance/pin di
Poisson's Ratio	0.33	0.33	Estimated from trends i
Fatigue Strength	150 MPa	21800 psi	5 E+8 cycles unn Moore rc
Machinability	30 %	30 %	0-100 Scale of Alumi
Shear Modulus	26.4 GPa	3830 ksi	
Shear Strength	170 MPa	24700 psi	
Compressive Modulus	71.7 GPa	10400 ksi	
Electrical Properties			
Electrical Resistivity	5.9e-006 ohm-cm	5.9e-006 ohm-cm	

Thermal Properties

CTE, linear 20°C	23.8 μm/m-°C	13.2 μin/in-°F	
CTE, linear 250°C	26 μm/m-°C	14.4 μin/in-°F	Average over the ran
Heat Capacity	0.9 J/g-°C	0.215 BTU/lb-°F	
Thermal Conductivity	117 W/m-K	812 BTU-in/hr-ft_-°F	
Melting Point	591 - 638 °C	1100 - 1180 °F	
Liquidus	638 °C	1180 °F	
Solidus	591 °C	1100 °F	

References are available for this material.

MatWeb.com, The Online Materials Database
Magnesium AZ31B-H24, Hard Rolled Sheet

Subcategory: Magnesium Alloy; Metal; Nonferrous Metal

Key Words: UNS M11311; Mg

Component	Wt.	Component	Wt.	Component	W

Material Notes:
Mg content calculated as balance. AZ31B and AZ31C have the same nominal cc and differ only in specification ranges. Medium strength.

Hardness, Brinell	73	73	500 kg lo
Hardness, Knoop	96	96	Estir
Tensile Strength, Ultimate	290 MPa	42100 psi	
Tensile Strength, Yield	220 MPa	31900 psi	at 0
Elongation at Break	15 %	15 %	
Modulus of Elasticity	45 GPa	6530 ksi	
Compressive Yield Strength	180 MPa	26100 psi	at (
Ultimate Bearing Strength	495 MPa	71800 psi	
Bearing Yield Strength	325 MPa	47100 psi	
Poisson's Ratio	0.35	0.35	
Machinability	100 %	100 %	Relat
Shear Modulus	17 GPa	2470 ksi	
Shear Strength	160 MPa	23200 psi	

Electrical Properties

Electrical Resistivity	9.2e-006 ohm-cm	9.2e-006 ohm-cm

Thermal Properties

Heat of Fusion	340 J/g	146 BTU/lb	
CTE, linear 20°C	26 µm/m-°C	14.4 µin/in-°F	from 0-
CTE, linear 100°C	27 µm/m-°C	15 µin/in-°F	2 Estir similar
Heat Capacity	1 J/g-°C	0.239 BTU/lb-°F	
Thermal Conductivity	96 W/m-K	666 BTU-in/hr-ft_-°F	
Melting Point	605 - 630 °C	1120 - 1170 °F	
Solidus	605 °C	1120 °F	
Liquidus	630 °C	1170 °F	

Processing Properties

Processing Temperature	230 - 425 °C	446 - 797 °F	H
Processing Temperature	345 °C	653 °F	Anne

References are available for this material.

.

MatWeb.com, The Online Materials Database
Titanium Grade 2, Annealed

Subcategory: Metal; Nonferrous Metal; Titanium Alloy; Unalloyed/Modified Titaniu

Close Analogs: Titanium Grades 1,2,3,4,7,11,and 12 are all considered unalloye
have similar mechanical properties.

Key Words: ASTM Grade 2; UNS R50400, CP titanium, C.P. titanium alloy

Component	Wt. %

Material Notes:
Information provided by Allvac and the references.

Applications: Airframe components, cryogenic vessels, heat exchangers, CPI eq
condenser tubing, pickling baskets. Sample was annealed 2 hr at 700°C.

Modulus of Elasticity	102 GPa	14800 ksi	
Compressive Yield Strength	340 MPa	49300 psi	
Notched Tensile Strength	720 MPa	104000 psi	concentrat
Ultimate Bearing Strength	930 MPa	135000 psi	
Bearing Yield Strength	660 MPa	95700 psi	
Poisson's Ratio	0.34	0.34	
Charpy Impact	65 J	47.9 ft-lb	
Fatigue Strength	240 MPa	34800 psi	at 1E+ (stress c
Fatigue Strength	280 MPa	40600 psi	1
Shear Modulus	38 GPa	5510 ksi	
Shear Strength	380 MPa	55100 psi	Ul

Electrical Properties

Electrical Resistivity	5.2e-005 ohm-cm	5.2e-005 ohm-cm	

Thermal Properties

Heat of Fusion	325 J/g	140 BTU/lb	Hig
CTE, linear 20°C	8.6 μm/m-°C	4.78 μin/in-°F	
CTE, linear 250°C	9.2 μm/m-°C	5.11 μin/in-°F	Uns treatm over the ra
Heat Capacity	0.523 J/g-°C	0.125 BTU/lb-°F	
Thermal Conductivity	16.4 W/m-K	114 BTU-in/hr-ft_-°F	
Melting Point	Max 1665 °C	Max 3030 °F	
Liquidus	1665 °C	3030 °F	
Beta Transus	913 °C	1680 °F	

Optical Properties

Emissivity (0-1)	0.3	0.3	High

Reflection Coefficient, Visible (0-1)	0.56	0.56	Hi

References are available for this material.

.

Appendix 2: Change Controls for the LH2 target

Dear Folks: Enclosed please find a "change control" request from Indiana University for the NPDG liquid hydrogen target and gas handling system. This change control request covers 3 areas: (1) a change in the target vessel material from aluminum/magnesium to titanium, (2) a clarification of the meaning of the requirement to surround all parts of the target vessel inside the cave in a helium jacket, and (3) a request to consider the possibility of allowing the hydrogen gas bottles for target filling to be located inside ER-2 near the experimental cave inside a vented enclosure. Based on our analysis, we believe that all 3 of these changes would increase the overall safety of the target system.

- **Change in the LH2 vessel material from a flanged aluminum/magnesium vessel to an all-welded titanium vessel**.

We propose to construct the LH2 target vessel from pure titanium Grade 2. The geometry (shape and wall thickness) of the vessel in the areas which determine its pressure rating would be the same as the geometry of the vessel design recommended by the ARES Corporation based on finite element analysis. However the safety of the target would be improved by (a) the elimination of the vacuum seal between the aluminum and the magnesium, (b) the greater strength of titanium relative to aluminum/magnesium.

High strength titanium alloys are unacceptable due to the possibility of hydrogen embrittlement and it was for this reason that we did not propose titanium originally. Since the NPDG safety meeting, however, we have discovered that commercially pure Grade 2 titanium vessels were routinely used by NASA in their Apollo-Saturn missions to store liquid hydrogen. Furthermore, titanium Grade 2 is less susceptible to hydrogen embrittlement than certain stainless steel alloys which are also routinely used by NASA to store liquid hydrogen. The reason why it is safe to store hydrogen in titanium is because the tough oxide layer that forms on titanium surfaces exposed to atmosphere strongly suppresses the permeation of hydrogen into the metal. With proper precautions, designed to maintain the integrity of this oxide layer (electropolishing/anodizing the internal surface to establish a smooth internal surface area and exposure of the inner vessel to atmosphere when it is at room temperature to ensure oxide layer formation), a titanium vessel can be made safe from hydrogen embrittlement. Furthermore, we have discovered that seamless titanium tubing in the diameter required for the target is commercially available. This eliminates the necessity for a longitudinal weld along the target and therefore the total length of weld seams would be comparable to that required in the original aluminum portion of the vessel. Details are included in Appendix A.

- **Clarify the meaning of the helium gas jacket requirement.**

One of the features agreed to at the safety meeting was the need to surround all parts of the main vacuum vessel inside the experimental cave by a helium jacket, and we at IUCF certainly agree to this principle. Our question now is one of interpretation: whether or not it is necessary for the helium gas to cover paths which pass through non-welded, seal-free portions of solid material. The problem is that, strictly speaking, this is impossible if there is to be any mechanical support between the helium jacket and the vacuum jacket.

Consider for example the aluminum braces that are needed in the annular space between the vacuum vessel and helium jackets to strengthen the vessel for the accident scenarios. These braces would be immersed in the helium gas in the jacket, but would be touching both the outer vacuum can and the inner helium jacket. Strictly speaking, there then would exist a path through the vacuum wall, the inside of the brace material, and the helium jacket; a path not blocked by helium gas.

The safety committee did not object to the aluminum braces despite this possibility. Presumably the reason was because they implicitly accepted that it was not necessary for the helium gas to cover a path
through non-welded, seal-free solid material. Indeed without this assumption it is impossible to mechanically support the helium jacket.

The same issue arises in the support of the cryostat as a whole. Unless the main vacuum can is to be freely-floating in space, it must somewhere be mechanically connected to the helium jacket for support.
But then the same issue arises: this introduces a path through the solid which is not blocked by helium gas. Similar issues arise with the cryo-refrigerator. Although the surface it presents to the inside of the main vacuum possesses no welds or seals, if one argues that one must surround solid paths with helium then it is necessary to separately bag the outside of the motor housing etc. of the refrigerator, which would make it difficult to operate.

So our basic question to the committee is this: is it permissible to only surround with helium gas those portions of the main vacuum system which possess either welds or seals and not all solid material?

If the answer is strictly no, then we don't know how to support the main vacuum vessel.

If the answer is yes, then we can use an alternative design described and shown in the attached drawings The alternative design has advantages in assembly and construction yet it still allows all welds and seals to be completely surrounded by helium gas. Furthermore, we believe this alternative design improves target safety as explained below.

Note that, in this alternative "box" design concept as shown in Detail B of the drawing, one would introduce internal channels that would be filled with helium gas to surround all weld joints and seals, as opposed to an all-encompassing jacket.

There are other advantages to this design. In considering issues such as assembly, access, and possible revisions and repair to the target components inside of the main pressure/vacuum vessel, it became clear to us that such activities would be awkward (although doable) in the 'two cylinder' design. Thus the alternative design based on a box shape made of thick plates with grooves milled in the edges between the inner and outer weld joints was developed. This allows for helium to flow between the welds as well as between o-rings. The downstream side of the box is a full size lid with double o-ring grooves with a central helium channel. The lid allows full access to the refrigerator region, including liquefier, fill and vent piping, instrumentation & cabling, 80K shield and support structures. In the neutron beam region thin double domes are sealed to the lid as in the previous design.

To summarize the advantages of the box vs. cylindrical design for the vertical portion of the target vacuum chamber:

1. Access for assembly, revisions and repair is greatly simplified. The reliability of the target is thereby enhanced.
2. The central box region can be thick walled with internal and/or external bracing to make it much stronger than the central cylinder, making it a non-critical structural element with respect to accident scenarios.
3. Weld section thickness along inner and outer box joints can be much larger with increased strength, leak integrity and easy re-welding for leak repair.
4. While the overall mass would increase, actual fabrication and machining are simplified. Given that many if not all seal surfaces and o-ring grooves will need in any event to be milled after welding, the geometry and work holding options of the box vs. the cylinder are much improved.
5. Much more surface area is available for exiting the box at the top than in the double cylinder design. With the box design we intend to bring out the H2 vent, all instrumentation wiring and any other utilities inside a single jacketed cylinder so that everything remains in vacuum until outside the cave. By contrast, the annular surface available on the top flange in the original double cylinder design for the exit tubing makes it difficult to enclose all of the feedthroughs within one jacket without enlarging the diameter of the vertical portion of the main vacuum.

Possible disadvantages:

1. For walls of the same thickness, the box geometry is less optimal than a cylindrical shape for pressure vessel strength. But since this part of the target is outside of the neutron beam, thick walls and bracing can be used without penalty. Note that the walls are 1.25 inches thick.
2. The double o-ring groove in the box lid is ~3X the length of the bolted-on double dome, increasing leak risk and permeability. However, even this amount of o-ring surface length is not an uncommon size in typical vacuum vessels. Furthermore, because helium permeation through the o-ring seals is an issue with either chamber design, we plan to use indium seals on the inner grooves.
3. Total weight of the target is increased to perhaps 200lbs. as opposed to about 100lbs for the cylindrical design. This is still far less than the detector array, and within range of the linear bearings under consideration for target support and retraction. Mounting the target is probably simplified somewhat with the flat lower surface of the box design.

Please see the included pdf files for the general idea of the design.

- **Allow gas bottles for the target to be located in ER-2 inside a vented cabinet.**

When supply gas issues were discussed at the safety meeting there were two alternatives considered: (a) a series of gas bottles outside ER-2 coupled with a line to the experimental cave, (b) a storage tank. The safety committee asked us to consider (b) because it was not satisfied that (a) is the safest solution mainly due to the possibility of operator error in changing the bottles.

We have considered (b) and concluded that in practice it is even less safe than (a). The main reason is the impractically large size that would be required for the dump tank to hold 20 liters of liquid hydrogen that has converted to room temperature gas at an acceptably low pressure.

In addition both (a) and (b) require a long H2 gas line from outside ER2 to the experiment. Unless this line can be made sufficiently clean, the hydrogen line would need to incorporate a palladium leak purifier near the target location. To get a high enough flow rate for filling the target the palladium purifier would need to be operated at a pressure of 200 psi on the supply end. Having such a high pressure in a long supply line is not the best idea from a safety point of view.

We have considered two other design variants in an attempt to increase safety: (1) eliminating gas bottles altogether by using a commercial hydrogen gas generator located on top of the cave to make H2 gas on demand by electrolysis of de-ionized water, (2) reducing the length of the supply line and eliminating the need for the high internal pressure associated with palladium leak purification by locating near the hut hydrogen gas bottles of 6-9's purity in a commercially-available vented enclosure.

We believe that (2) is the safest and most reliable option for the following reasons:

(6) Total length of the H2 gas supply line from bottles to target is much shorter. Gas lines can more easily be directed to avoid possible interference with other devices in ER2 such as cranes etc.

(2) Gas bottles would be isolated from the rest of ER-2 by a commercially-available enclosure with a vent stack. This vent stack could be merged into the main vent stack for the target.

(3) Use of 6 9's purity gas combined with short distance to target would eliminate the need to use a palladium purifier for target filling outside the gas bottle enclosure (a purifier may still be included inside). This eliminates the need for a high pressure line outside the gas bottle enclosure.

(4) Plumbing and controls for automatic switching of target filling from multiple H2 bottles on a manifold
exist. Fixtures for pumping out the dead space between the H2 bottle and the valve exist. This mitigates to some extent the safety concern over bottle changeover during target filling.

Appendix B includes an analysis of the pros and cons of the latter two options.

Appendix A: Arguments for using Titanium as Material for LH2 Target Vessel

Hermann Nann

Titanium is being widely used in hydrogen-containing environments because of its high corrosion resistance. NASA report 1740.16, Safety Standard for Hydrogen and Hydrogen Systems, (Ref. 1) gives in Table A5-1 a list of materials acceptable for use in hydrogen service. Titanium is one of the materials listed to be suitable for service of gaseous, liquid, and slosh hydrogen. The NASA Apollo-Saturn Project used in its lunar module two spherical dewar-type titanium tanks to store cryogenic hydrogen (Ref. 2). These tanks were built by Beech Aircraft Corp., Boulder, CO. Each tank had a capacity of 28 pounds of usable liquid hydrogen. Their inner wall thickness was 0.046 inch and the rupture pressure was 450 psi.

The remainder of this note discusses relevant information on the physics and engineering of hydrogen embrittlement in metals such as titanium. Our conclusion is that the successful use of titanium storage vessels for liquid hydrogen is confirmed by studies performed in the literature and that there is nothing unique about the environment of the hydrogen target in NPDGamma which will change this conclusion.

Hydrogen embrittlement (HE) is the deleterious effect of hydrogen on the mechanical properties of its containment vessel. It has been observed in almost every structural metal and alloy tested. Inspecting Table A5.8 of Ref. 1, which summarizes the susceptibility of some materials to hydrogen at 68.9 MPa and 295 K, shows that pure titanium is slightly less susceptible to HE than 304L stainless steel which is customarily used for liquid hydrogen dewars and piping. In general, embrittlement problems are not considered severe for containers at cryogenic temperatures. Furthermore, the cryogenic container will be thermally cycled between room temperature and 20K and will undergo thermal expansion and contraction. Since titanium has a very low coefficient of thermal expansion, stresses occurring during temperature changes are much less severe than for other materials.

Titanium develops very stable surface oxides with high integrity, tenacity, and good adherence. This surface oxide film acts as a highly effective barrier to hydrogen (just like the oxide film on aluminum). Penetration can only occur when this protective film is disrupted or broken down chemically or electro-chemically. Penetration diffusion of hydrogen into titanium is very slow at temperatures below 80°C, except where high residual or applied tensile stresses exist. At temperatures below 80°C, hydride formation is normally restricted to the surface layers of the metal and experience in such cases indicates that this has little or no serious effect on the performance of the metal. Studies have shown (Ref. 3) that grade 2 titanium is much less susceptible to HE than grade 3 titanium where hydrides were observed in its interior. Titanium alloys are more susceptible to HE than the pure metal.

Surface finish of the titanium after machining has a marked influence on HE. Studies of various surface treatments that showed retarded absorption of hydrogen also have shown inhibitions of HE (see Ref. 6). Hydrogen permeation measurements and tritium intake studies (Ref. 5) indicate that the as-machined surface (64-rms finish) is much more permeable to hydrogen than polished surfaces. Studies (Ref. 4) showed that sandblasting rendered the titanium surface more susceptible to hydrogen penetration. However, pickling and anodizing restored almost complete immunity to HE. Ref. 7 showed that titanium coatings are used to protect 304 stainless steel from embrittlement.

Welds are especially susceptible to HE in all hydrogen environments. However, post-weld annealing will restore favorable microstructure. Weldments and heat affected zones of titanium exhibit HE resistance equal to their base metal counterparts. This is attributable to the protective oxide layer which forms on the titanium surfaces despite microstructural differences. Electrical discharge machining processes should not be used since they can introduce hydrogen into a machined component.

Atomic hydrogen, which will be formed in the target at small concentrations by gamma irradiation, will not reduce the titanium surface oxide layer. The molar enthalpy of formation of TiO_2 is $-944.7\ kJ \cdot mol^{-1}$ compared to that of $H_2O(l)$ of $-285 kJ \cdot mol^{-1}$.

References:

1.) NASA Report NSS 1740.16 (already in the list of references of the technical report)
2.) http://www.apollosaturn.com/asnr/power1.htm
3.) Z.F. Wang, C.L. Briant, and K.S.Kumar, Corrosion 54, 553 (1998)
4.) L.C. Covington, Corrosion 35, 378 (1979)
5.) G.R. Caskey, Jr., Material Sci. and Eng. 14, 109 (1974)
6.) F.J. Edeskuty and N.N. Sheheen, LANL Report LA-7820-PR
7.) M.R. Louthan, Jr., G.R. Caskey, Jr., J.A. Donovan, and D.E. Rawl, Jr., Material Sci. and Eng., 10, 357 (1972)

Appendix B: Advantages and Disadvantages of two new proposed improvements in the NPDG gas handling system concept.

HOGEN 40 H_2 Generator vs. Bottles of Research Grade H_2 Bill Lozowski 5/1/02

HOGEN 40 Pros:

1) It delivers in 5 to 30 minutes 99.999 % H_2 at a maximum rate of 17 SLM, fast enough to fill the target.
2) A H_2 purifier will probably not be necessary since it has a palladium leak inside it.
3) A manifold and a delivery line for bottled H_2 is not part of the H_2 system for the target.

HOGEN 40 Cons:

1) 50 k$ price
2) It requires a vent for up to 44 SCFH of wet H_2 and a vent for up to 9.5 SLM O_2. The vent ends must be protected from freezing conditions.
3) For reasonable life of the internal ion-exchange resin, ≥ 10 MΩ-cm water at ≥ 2-bar line pressure is required. Unit will shut down if resistance drops to 1 MΩ-cm.
4) It requires a drain for the DI water.
5) H_2 is supplied at 200 psig for no-flow or low-flow conditions. Downstream pressure regulation is necessary.
6) It requires floor area of 91” by 72.”
7) It requires 8 kVA service (220-240 V, 1 phase, 60 A).
8) A provision for remote control is not provided.
9) For periods of non-use longer than 3 months, a cell-hydration procedure (5 minutes) must be performed to avoid destruction of the 11 k$ Proton Exchange Membrane (PEM) cell stack.

Bottled H_2 System Pros:

1) Research grade is 99.9999 % H_2, i.e., 1 ppm vs. 10 ppm contaminates for the HOGEN 40. With the usual precautions employed to maintain the gas purity, a H_2 purifier would not be necessary.
2) If a H_2 purifier is employed, it could be positioned near the supply bottles. Thus, the H_2 pressure in the long supply line to the target could be regulated to a value near the desired 1.25 bar.

3) No H_2 lines in the tent would be at 200 psig.
4) It (the 6-9's gas) is comparably inexpensive.
5) Gas manifolds are commercially available to assemble an uninterrupted supply of H_2 in vented cabinets.
6) Such a manifold system would eventually be needed to run LD_2 in the target for a future experiment in n+D->T+gamma (awkward to supply a HOGEN with de-ionized D2O).

Bottled H_2 System Cons:

1) About 3.4 bottles of research grade would be needed to fill the target. An additional 8(?) bottles would need to be immediately available.
2) If a H_2 purifier positioned near the target were decided to be a safety priority and the bottles could not be positioned near the hut, the long H_2 supply line to the purifier would be at 200 psig.
3) There is more opportunity for operator error to introduce air into the supply line. However commercially available specialized connectors exist for pumping out the space between the bottle and the valve.
4) The bottled H2 system will require a solid particle filter to protect against particles from the internal surface of the supply bottles from entering the gas handling system. However, the impedance of this filter will not lead to a significant pressure difference in the supply line.

Dear Change Control committee:

IUCF requests a change contol for one of the two refrigerators on the LH2 target.

Originally the plan was to use two Gifford-McMahon refrigerators from CVI with special-ordered stainless steel parts reduce magnetic field gradients from the moving parts. We have one of these refrigerators in hand
and it has passed all required tests (cooling power, magnetic fields, safety committee issues) required for operation in the experiment. The remaining (possible) concern is the mechanical vibrations that this device might transmit to the target vessel. Although most of the vibrations are in the head of the vessel and will probably be absorbed to some extent in the coupling to the main vacuum chamber, there may be some vibrations at the cold heads.

However we recently have obtained a new so-called "pulse tube" cryorefrigerator from Cryomech. We believe that this refrigerator is either comparable or superior to theCVI refrigerator in all areas relevant to the experiment. In particular it produces essentially no mechanical vibration. So our request is to use this refrigerator in addition to the CVI refrigerator as the two refrigerators for the target.

here is a comparison of the two devices:

(1) Reliability

The reliability of the Cryomech from experience (~40,000 hours) is superior to that of the CVI (~25,000 hours). The basic reason is that unlike a Gifford-McMahon refrigerator, the pulse tube refrigerator has no cold moving parts.

(2) Cooling Power

We have measured the cooling powers of both refrigerators with the following results:

type	Stage 1, 17K	Stage 2
Cryomech	7W	
CVI	8.5W	

The cooling power of the Cryomech is ~15% smaller than that of the CVI in the operating range. This results in approximately the same increase in filling time for the liquid.

(3) Magnetism

The CVI refrigerator possesses a 60Hz moving part that is slightly magnetic. By special order we had this piece made from stainless steel and bounded the disturbance in the field caused by this part and the motor to be more than an order of magnitude below the value required for the experiment.

The Cryomech refrigerator has no moving magnetic parts except for the motor, which creates a field that is smaller than that from the CVI. Other magnetic componets are the Aeroquip fittings where the He lines attach and the electrical fitting for the motor. The field from the DC stepper-motor inside the Cryomech housing is smaller than that from the CVI motor.

(4) LH2 Safety

Both refrigerators present helium gas between atmosphere and the main vacuum throughout the refrigerator body. Therefore both pumps meet the safety requirement of helium gas containment of the vacuum chamber.

Both refrigerators operate using helium gas compressors that will be located on top of the experimental cave.

(5) Ortho-para regeneration

Once or twice over the course of the experiment it may become necessary to heat the material in the ortho-para converter cell to regenerate its conversion surface. The max temperature that the second stage can tolerate is 70C for the Cryomech, 150C for the CVI. The material needs to be heated to about 120C. We are designing the thermal connections between the ortho-para converter and the refrigerators in such a way that, if necessary for this relatively rare procedure, the thermal connection can be broken without disconnecting the inlet and outlet tubing.

(6) Vibration

The CVI refrigerator produces 60Hz vibrations during operation. The Cryomech refrigerator has essentially no vibrations that can easily be sensed by human touch. It produces some sound at the ~1Hz frequency with which the helium gas is looped through the device.

(7) Other implications

Although we require both refrigerators to operate during target liquification and ortho-para conversion, it is possible that only one of the refrigerators may be required for continuous operation during data taking. The use of the pulse tube refrigerator allows for the possibility of operating the target with essentially no vibrations.

Mike Snow
Bill Lozowski

IUCF

Dear Change Control Committee:

This note is to summarize the current status and to request a change control on the target to use an all-welded Al vessel for the reasons outlined below.

Advantages of all welded vessel are: (1) greater safety, (2) no need to
redo the finite element calculations of ARES done for the LANL LH2 safety committee.
Disadvantage: increase in size of total systematic effect from polarized n capture on vessel by about a factor of 2.

Advantage of the 2-piece assembly is that we can insert the Li plastic.
Disadvantages of 2-piece target are: (1) less safety (reliability of seal), (2) possible need to redo finite element calculations (this is not clear to us: we have a preliminary design for a 2-piece assembly which we believe would obey the recommendations of the FEA safety/stress calculations involving a seal in the rear of the target chamber as opposed to the front. But then the question is will the safety committee agree. We would need to ask and this would take time), (3) 2-piece assembly introduces more matter in the vessel due to the need of an external clamp for the seal.

We would like to make this decision on the one versus two piece target soon because it would affect the designs of cryostat radiation shields/thermal links. We would like to be able to design these in such a way that they can accomodate both an Al target or a Ti target.

The only other material one can imagine making the taregt out of is zirconium. There is Russian

data and experience on the welding of Zirconium and its operation in a low temperature environment (it was used as the material for the neutron cold source at PNPI).
We have shied away from this possibility because it is not a material that is mentioned in the ASME pressure vessel literature (both Al and Ti are mentioned) and therefore we are concerned that the safety committee may not accept it for this reason alone or they may require extensive and time-consuming tests. We have not looked into US vendors who could fabricate the vessel out of Zr or do the welding.

Mike Snow

Dear Folks: Enclosed is a request from Indiana University for a change in the design of the vacuum vessel for the NPDG liquid hydrogen target. Based on our analysis, we believe that this change would increase the overall safety of the target system. For comparison by the Change Control Committee, detailed drawings of the original vacuum vessel design are included in this request.

One of the features agreed to at the safety meeting was the need to surround all parts of the main vacuum vessel inside the experimental cave by a helium jacket, and we at IUCF certainly agree to this principle. Our question now is one of interpretation: whether or not it is necessary for the helium gas to cover paths that pass through non-welded, seal-free portions of solid material. The problem is that, strictly speaking, this is impossible if there is to be any mechanical support between the helium jacket and the vacuum jacket.

Consider for example the aluminum braces that are needed in the annular space between the vacuum vessel and helium jackets to strengthen the vessel for the accident scenarios. These braces would be immersed in the helium gas in the jacket, but would be touching both the outer vacuum can and the inner helium jacket. Strictly speaking, there then would exist a path through the vacuum wall, the inside of the brace material, and the helium jacket; a path not blocked by helium gas.

The safety committee did not object to the aluminum braces despite this possibility. Presumably the reason was because they implicitly accepted that it was not necessary for the helium gas to cover a path through non-welded, seal-free solid material. Indeed without this assumption it is impossible to mechanically support the helium jacket.

The same issue arises in the support of the cryostat as a whole. Unless the main vacuum can is to be freely floating in space, it must somewhere be mechanically connected to the helium jacket for support.
But then the same issue arises: this introduces a path through the solid that is not blocked by helium gas. Similar issues arise with the cryo-refrigerator. Although the surface it presents to the inside of the main vacuum possesses no welds or seals, if one argues that one must surround solid paths with helium then it is necessary to separately bag the outside of the motor housing etc. of the refrigerator, which would make it difficult to operate.

So our basic question to the committee is this: is it permissible to surround with helium gas only those portions of the main vacuum system which possess either welds or seals and not all solid material?

If the answer is strictly no, then we don't know how to support the main vacuum vessel.

If the answer is yes, then we can use an alternative design described and shown in the attached drawings. The alternative design has advantages in assembly and construction yet it still allows all welds and seals to be completely surrounded by helium gas. In our judgment, the Committee should agree that the non-welded, solid aluminum plates and pipes of the alternative design will ensure there will be no leaks induced either by material defects or pressure excursions. Furthermore, we believe this design improves target safety as explained below.

Note that, in this alternative "box" design concept as shown in Detail B of the drawing, one would introduce internal channels that would be filled with helium gas to surround all weld joints and seals, as opposed to an all-encompassing jacket.

There are other advantages to this design. In considering issues such as assembly, access, and possible revisions and repair to the target components inside of the main pressure/vacuum vessel, it became clear to us that such activities would be awkward (although doable) in the 'two cylinder' design. Thus the alternative design was developed based on a box shape made of thick plates with grooves milled in the edges between the inner and outer weld joints. This allows for helium to flow between the welds as well as between o-rings. The downstream side of the box is a full size lid with double o-ring grooves with a central helium channel. The lid allows full access to the refrigerator region, including liquefier, fill and vent piping, instrumentation & cabling, 80K shield and support structures. In the region of the neutron beam, thin double domes are sealed to the lid as in the previous design.

To summarize the advantages of the box vs. cylindrical design for the vertical portion of the target vacuum chamber:

1. Access for assembly, revisions and repair is greatly simplified. The reliability of the target is thereby enhanced.
2. The central box region is thick walled with internal and/or external bracing to make it much stronger than the central cylinder, making it a non-critical structural element with respect to accident scenarios.
3. Weld section thickness along inner and outer box joints is much larger, providing increased strength, wall integrity against leaks and easy re-welding for leak repair.
6. While the overall mass would increase, actual fabrication and machining are simplified. Given that many if not all seal surfaces and o-ring grooves of either design scenario will need to be milled after welding, the geometry and work holding options of the box vs. the cylinder are much improved.
7. Much more surface area is available for exiting the box at the top than in the double cylinder

design. With the box design we intend to bring out the H_2 vent, all instrumentation wiring and any other utilities inside a single jacketed cylinder, so that everything remains in vacuum until outside the cave. By contrast, the annular surface available for exit tubing on the top flange in the original double cylinder design makes it difficult to enclose all of the feedthroughs within one jacket without enlarging the diameter of the vertical portion of the main vacuum.

Possible disadvantages:

1. For walls of the same thickness, the box geometry is less optimal than a cylindrical shape for pressure vessel strength. But since this part of the target is outside of the neutron beam, thick walls and bracing can be used without penalty. Note that the walls of the box are 1.25 inches thick.
4. The double o-ring groove in the box lid is ~3X the length of the bolted-on double dome construction, increasing leak risk and permeability to helium. However, even this amount of o-ring surface length is not an uncommon size in typical vacuum vessels. Furthermore, the inner grooves will be sealed with indium wire because helium permeation through the o-ring seals is an issue with either chamber design.
5. The total weight of the target is increased to perhaps 200lbs. as opposed to about 100lbs for the cylindrical design. This is still far less than the detector array, and within range of the linear bearings under consideration for target support and retraction. Mounting of the target is probably simplified somewhat with the flat lower surface of the box design.

Dear Safety Committee members:

We want to make a change control request on the requirement of radiography of the welds on the main vacuum system for the NPDG liquid hydrogen target. The original recommendation of the safety committee for radiography for these welds was based on the type of welds (full penetration welds) in the design that the safety committee had available at that time of the review. In the meantime, however, the design changes to the main vacuum system involved a change in the type of welds to fillet welds, for which the ASME code states that radiography is not applicable. We therefore request the permission of the safety committee to forego what we understand to be a useless radiographic examination of the fillet welds on the main vacuum chamber.

The original report of the LH2 safety committee requested radiography of welds for the vacuum chamber and target chamber. This recommendation was based on the design of the main vacuum chamber presented at the time, which involved helium-jacketed cylinders. Later the safety committee approved a modified design of the main vacuum chamber in which gas channels around the weld joints were substituted for an all-encompassing jacket and in which the strength of the target was increased by machining a portion of the chamber out of a single piece of aluminum, thereby reducing the number of welds. In addition, the wall thickness of the aluminum was increased in the weld areas to increase strength.

In the approved modified design, the cylindrical part of the main vacuum chamber is joined to the thick-walled box by double full-fillet welds. Such welds are allowed by the ASME code and no radiography is required when the joint design complies with Table UW-12 (c) in the Code. Table UW-12 also states that neither full nor spot radiographic examination is applicable to fillet weld joints. Fillet welds are not full penetration welds, and the purpose of radiography is to verify full penetration welds. Our strength calculations show that the wall thickness of 0.125 inch for the cylindrical part of the vacuum vessel and a weld efficiency of 0.55 (from table UW-12) gives a calculated maximum allowable pressure of 94 psia. The vacuum chamber has successfully been pressure tested to 95 psia.

In parallel with this result for the pressure test and redesign of the vacuum vessel, there have also been changes to the gas handling system design which lower the working pressure of the vessel. With the increase in the inner diameter of the pressure relief line for the vacuum vessel from 2.5 to 3.75 inch, we estimate that the outlet pressure for a worst-case accident scenario has been lowered to less than 25 psia (calculations based on the Williamson Jlab report referred to in the LH2 Engineering document). 25 psia is now our maximum operating pressure. The set points for two parallel rupture disks in the pressure relief line from the vacuum vessel are now 15 psid and 70 psid. The vacuum vessel was pressure tested at 80 psid, which is 1.15 times 70 psid. Traditionally, the ASME code requires a pressure test of 1.1 times the MAWP of a vessel

Radiography only has meaning for full penetration welds. The welds in the new main vacuum chamber design are fillet welds. Fillet welds are not radiographed because the primary reason for radiography is to verify complete penetration of the weld. A radiograph of a fillet weld will simply show a line of incomplete penetration. This observation is simply not relevant for evaluating the safety of a fillet weld.

We therefore assert that radiography is not required for the main vacuum chamber of the LH2 target as designed and ask for the safety committee to allow us to forego what we and the Code assert will be a pointless radiograph of the fillet welds on the LH2 vacuum vessel. Of course radiography is being performed on the LH2 target vessel itself as required.

<u>*Appendix 3:*</u> (H. Nann, 6-6-01): Calculations of Flow Rates through the vent lines in the event of catastrophic vacuum or target failure:
The following are results of calculations based on the formulae and procedures of the Bates Internal Report # 90–02 [21] and the Crane Technical Report No. 410 [11] for various mass flow rates and inner diameters (I.D.) of the vent pipe. The vent line contains all pipes and bends up to the main exhaust pipe, including the pressure relief valve. The rate of mass flow through pipes, valves and fittings is given by the Darcy formula

$$w = 0.1192 Y d^2 \sqrt{p_1 (p_1 - p_2) \left(\frac{M}{KT} \right)}$$

where w = mass flow rate [lb/s]
p_1 = inlet (upstream) pressure [psia]
p_2 = outlet (downstream) pressure [psia]
d = inner diameter of vent pipe [inch]
Y = net expansion factor for compressible flow through orifices, nozzles, or pipe (The functional dependence of Y vs $(p_1 - p_2)/p_1$ is given in the charts on page A-22 of the Crane Technical Report No. 410 [11])
K = total resistance coefficient for the vent system
T = absolute temperature of the flowing gas [K]
M = molecular mass of the gas [g/mol]

Maximum Pressure in the Target Flask due to Catastrophic Failure of Vacuum

Assume: Flow temperature: $T = 293$ K, taken at the warmest point in the relief system. This will overestimate the inlet pressure p_1, but this will be an error on the side of safety. Outlet pressure: $p_2 = 15$ psia, venting to air at standard atmospheric pressure. Resistance coefficient (specified for a reference I.D. of 1.5 inch of smooth pipe; friction factor f = 0.021):

Component	L/d	Resistance coefficient K
Pipe, 10 feet long, 1.5 inch I.D.	80.0	1.68
5 - 90^o elbows		3.15
Sudden enlargement, d/D = _		0.56
Relief valve		4.20
TOTAL		9.59

Use $K = 10$

Results:

Mass flow rate [lb/s]	$w =$	0.05	0.10	0.10	0.10	0.15	0.20	0.30	0.30
ID of vent pipe [inch]	$d =$	1.0	1.0	1.125	1.5	1.125	1.5	1.5	1.75
Sonic flow rate [lb/s]	$w_{sonic} =$	0.13	0.13	0.16	0.29	0.16	0.29	0.29	0.40
Inlet pressure [psia]	$p_1 =$	28.4	52.5	42.1	26.0	61.9	47.0	69.5	51.4

Maximum Pressure in the Vacuum Vessel due to Rupture of LH_2 Flask

Assume: Flow temperature: $T = 293$ K
Outlet pressure: $p_2 = 15$ psia
Resistance coefficient: $K = 10$

Here the LH_2 is in contact with larger warm surface area $\Rightarrow$ larger boil-off rate and thus larger mass flow rate.

Results:

Mass flow rate [lb/s]	$w =$	0.5	0.5	0.75
ID of vent pipe [inch]	$d =$	2.0	2.5	2.5
Sonic flow rate [lb/s]	$w_{sonic} =$	0.52	0.82	0.82
Inlet pressure [psia]	$p_1 =$	65.2	42.6	62.7

<u>*Appendix 4:*</u> (M. Gericke, 7-1-01, modified by M. Snow, 6-1-03): Gas Handling System Operating

Procedures

The following set procedures must be performed with the gas handling system before during, and after filling with liquid hydrogen: (1) leak checking the target and gas handling system, (2) purging the lines with various gases before target filling, (4) filling the target, (5) steady-state target operation, (6) controlled venting of the target. In addition, there are independent procedures for other operations on the GHS. First we describe the procedures that are closely associated with target filling. Then we outline the other procedures.

leak checking and purging

(1) Starting state: pump out entire system, including target vessel, main vacuum system, hydrogen fill system up to valves V101, V103, and V105, on the H2 supply bottles, which are closed,.No helium in vent line. Turn on RGA and verify that it is working properly as a helium leak detector.

(2) Close V208, V128 to isolate GHS from main vacuum and target for leak check of GHS. Spray helium gas on the outside of all components of the GHS accessible from outside the cave. Move objects such as valves on and off to verify that there are no external leaks correlated with mechanical motion. Repeat until no leaks are found.

(3) Open V128 and V208. Spray helium gas on the outside of all components inside the cave. Repeat until no leaks are found.

(4) Close V405. Open V401 and V402. Verify that there are no leaks into the weld joints surrounded by helium channels. Leave helium gas in the lines after filling. Close V128 and V208.

(5) Close V107, V108, and V111. Introduce helium gas into vent line to check for leak-throughs in RV104, RD101, RV103, RV102, RV101, and V110

(6) Connect helium gas to V112 and add gas. Check for leak-through in V110, V107, and V108, and then V113. Continue in this manner to verify that none of the valves in the GHS leak through the valve seats.

The state reached at the end of this process should have helium gas in all areas of the GHS up to the RGA with valves V304, V301, V121, V119, V100, V204, V123,, V129, and V127 closed.

Connect the leak detector to V202, close V201. Leak check between V201 and V204. Use the RGA to leak check itself.

Open V128, V125, V120, V118, V117, V113, and V110 to put helium gas in the LH2 vessel. Open V204 to pump on GHS side of V208. Close V204, open V207 and V307. Open V208 and see if there is a leak from the LH2 target to the main vacuum.

Pump out the helium filled lines in all systems. Close V303, V100, V127, V204. and V405. Fill with helium gas again and pump out again. This procedure will pump and purge all lines twice.

Observe all pressure gauge readings throughout this procedure and verify that they are reading as expected.

Close V405. Fill helium gas into LH2 target channels.

Open V401, adjust V402. Fill vent line with helium gas.

ortho-para activation on GHS

Close V125, V122, V115, V114, V127. V100 Open V117, V118, V119, V303, V302. Turn off RGA.

Heat OPC to appropriate temperature. Record pressure on PT302. Continue until PT302 pressure increases due to heated gas evolution and then decreases and levels off at a new equilibrium. Stop heat, wait for OPC to cool. Continue pumping.

Open V125, V100, V115, V114. Pump out any residual gas in system.

Cool OPC. Monitor temperature until equilibrium is reached.

target filling

Close V128 and V208. Cool empty target to ~17K. Establish thermal control of target.
Pump on GHS to maintain cleanliness of system.

Open V105, V106, V108, V109,,, V115, V117, V120, , V125, V114. Adjust as necessary to establish static pressures of 200 psi on the inlet to the purifier. Activate purifier. Verify that all the pressure gauges are reading the correct values.

Open V128. Close V204. Fill. Occasionally monitor H2 in RGA1 by opening V304, V206, and V208.Any H2 readings beyond a set level on the RGA will stop the fill.

Monitor temperatures and pressures. Develop sufficiently robust criterion for full target by tests.

Close V105. V125, V100. Open V127, V122, V117, V114, V111 to pump out hydrogen in fill lines. Close V127.

Steady-State Operation

Monitor both H2 and He with RGA. V207, V208 open, V204 closed. Monitor pressures and compare to setpoints.

Target vent

Stop refrigerator operation. Close V204,. Open V205 as long as required to put 1 l-atm of argon gas into the main vacuum system. Close V204, V125. Wait for gas to escape through RV104.

Valve States during operations. The description of each step starts with a listing of the state of each valve in the system and all components which are involved in the specific operation. We start the description with a definition of a specific initial condition of the valves and pumps which suffices to perform only the specified operation. Since there are a large number of possible initial states from which one can safely perform the operation, we choose the valves to be closed initially in part to isolate the remainder of the system which is irrelevant to the task.Then each component or valve that changes state at least once during the step is shown in a table, listing the change of state it must undergo, in the correct sequence, as the table is read from left to right and top to bottom. The valve/component state list in the next step will reflect the changes performed on the various valves and components in the previous step. Those valves or components that will not change state during a particular step are not listed in the table, but are still repeated in the valve/component list. So no matter where one is in the sequence of steps the state list will always show the correct state that each component or valve should be in at that particular time. Except for the obvious exceptions, the procedures assume that one has already achieved a leak tight and clean state for the GHS and its components.

3. Bakeouts

3.1 GHS OPC Bakeout

State:
Open: none
Closed: V125, V123, V120, V119, V119A, V113, V116, V504, V403, V115, V124, V121, V304
MP101: on
LNTrap: empty

	V115	V122	MP101	Action
Step 1	Open	Open	On	Pump on OPC, OPC heater on
Step 2	Close	Close	Off	Stop Pumping, OPC heater off

3.2 H2 Purifier Bakeout

State:
Open: none
Closed: V120, V119A, V122, V109, V110, V111, V118, V116, V115, V504, V403, V119, V117, V113, V121, V304
MP101: on
H2 purifier: off

	V115	V119	V117	V113	V114	MP101	Action
Step 1	Open	Open	Open	Open	Open	On	Pump on Purifier
Step 2	Close	Close	Close	Close	Close	Off	Stop Pumping

3.3 LN trap Bakeout

State:
Open: none
Closed: V125, V122, V123, V120, V119, V119A, V113, V116, V117, V118, V504, V403, V115, V124, V121, V304
MP101: on
LNTrap: empty

	V115	V119	MP101	Action

	V115	V119	MP101	Action
Step 1	Open	Open	On	Pump on trap, trap heater on
Step 2	Close	Close	Off	Stop Pumping, trap heater off

4. GHS Helium Global Purge

State:

Closed: V101, V103, V105, V401, V501, V504, V403, V115, V112, V301, V306, V503, V404, V203, V202, V206, V123, V127, V118, V116, V304, V303, V129, V204
Open: all other valves

MP101: on
RGA: off
LNT: empty

	V401	V115	V504	V403	MP101	Action
Step 1	Open	Close	Close	Close	On	Fill GHS, target, main vacuum, vent stack with He
Step 2	Close	Open	Open	Open	Open	Pump He out of all volumes

5. Target He leak check

State:
Open: V303, V305, V307, V302, V207, V208 Closed: V125, V129, V127, V204, V306, V205, V206, V128
TP301: on
RGA: on

	V127	V128	V207	TP301	RGA	Action
Step 1	Open	Open	Open	On	On	Fill Target with He from V127, Leak check with RGA
Step 2	Close	Close	Close	On	On	Isolate RGA from helium

6. Target Pumpdown

State:
Open: V128, V125, V122, V302
Closed: V123, V127, V129, V116, V119, V119A, V115, V113, V303, V304, V121, V124, V126, V403, V504
TP301: on
MP301: on

	V115	V129	V125	TP301	MP301	Action
Step 1	Open	Close	Open	On	On	Pump target with MP301
Step2	Close	Open	Close	On	On	Pump target with TP301

7. Target filling

7.1 Preparation
7.1.1 Monitor H2 purity
State:
Open: V6,V9-V11,V13,V14,V16-V19,V21,V24-V29
Closed: V1-V5,V7,V8,V12,V15,V20,V22,V23,V30
TP1: off
TP2: on
RGA: off
LNT: empty

	V19	V23	V29	TP	V7	V5	RGA	LNT	Action
Step 1	Close	Open	Close	On	Close	Close	Off	empty	Pump on H2 Supply line via valve 23
Step 2	Close	Open	Close	On	Open	Open	Off	full	Open H2 supply, Monitor G4 (~10 E-4 Torr), Adjust R1
Step 3	Close	Open	Close	On	Open	Open	On	full	Monitor H2 purity on RGA

1. Continue main vacuum and Target Pumpdown and switch RGA to leak check on main vacuum

State:
Open: V5-V7,V9-V11,V13,V14,V16-V18,V21,V23-V28
Closed: V1-V4,V8,V12,V15,V19,V20,V22,29,V30
TP1: on
TP2: on
RGA: on
LNT: Full

	V5	RGA	V7	V23	V19	TP1	V24	V6	TP2	V2	V8	V15	Action
Step 1	Close	Off	Close	Close	Close	Off	Open	Close	Off	Open	Open	Open	Monitor P2 / G4
Step 2	Close	Off	Close	Close	Open	On	Open	Close	Off	Open	Open	Open	Pump on MV until P ~ 10E-4 Torr
Step 3	Close	On	Close	Close	Open	On	Open	Close	Off	Open	Open	Open	Check MV for leaks, Pump MV

7.2 Fill Target

State:
Open: V2,V8-V11,V13-V19,V21,V24-V28

Closed: V1,V3-V7,V12,V20,V22,V23,V29,V30
TP1: on
TP2: off
RGA: on
LNT: Full

	V9	V24	V5	V12	Action
Step 1	Close	Close	Close	Close	Monitor G4,P4,F1
Step 2	Close	Close	Open	Open	Adjust R1, Monitor G4,P4,F1

8. Continuous Target monitoring and leak checking

State:

Open: V2,V5,V8,V10-V19,V21,V25-V28
Closed: V1,V3,V4,V6,V7,V9,V20,V22-V24,V29,V30
TP1: on
TP2: off
RGA: on
LNT: Full

	V5	V10	V6	TP2	Action
Step 1	Close	Close	Open	On	Pump on H2 supply line. Shut off target cell
Step 2	Close	Close	Close	Off	Monitor MV for leaks and maintain vacuum

Final state:

Open: V2,V8,V11-V19,V21,V25-V28
Closed: V1,V3,V4-V7,V9,V20,V22-V24,V29,V30
TP1: on
TP2: off
RGA: on
LNT: Full